Naval EarthMap Observer (NEMO) Satellite

Thomas Wilson and Curtiss Davis

Naval Research Laboratory, 4555 Overlook Avenue, S.W., Washington, D.C. 20375

ABSTRACT

The Office of Naval Research (ONR) and the Naval Research Laboratory (NRL) have initiated the Hyperspectral Remote Sensing Technology (HRST) program to demonstrate the utility of a hyperspectral earth-imaging system to support Naval needs for characterization of the littoral regions of the world. One key component of the HRST program is the development of the Naval EarthMap Observer (NEMO) satellite system to provide a large hyperspectral data base. NEMO will carry the Coastal Ocean Imaging Spectrometer (COIS) which will provide images of littoral regions with 210 spectral channels over a bandpass of 0.4 to 2.5 µm. Since ocean environments have reflectances typically less than 5%, this system requires a very high signal-to-noise ratio (SNR). COIS will sample over a 30 km swath width with a 60 m Ground Sample Distance (GSD) with the ability to go to a 30 m GSD by utilizing the systems attitude control system to "nod" (i.e., use ground motion compensation to slow down the ground track of the field of view). Also included in the payload is a co-registered 5 m Panchromatic Imager (PIC) to provide simultaneous high spatial resolution imagery. A sun-synchronous, 97.81° inclination, circular orbit of 605 km allows continuous repeat coverage of the whole earth. One unique aspect of NEMO is an on-board processing system, a feature extraction and data compression software package developed by NRL called the Optical Real-Time Spectral Identification System (ORASIS). ORASIS employs a parallel, adaptive hyperspectral method for real time scene characterization, data reduction, background suppression, and target recognition. The use of ORASIS is essential for management of the massive amounts of data expected from the NEMO HSI system, and for developing Naval products under HRST.

The combined HSI and panchromatic images will provide critical phenomenology to aid in the operation of Naval systems in the littoral environment. The imagery can also satisfy a number of commercial and science community requirements for moderate spatial and high spectral resolution remote sensing data over land and water. Specific areas of interest for the Navy include bathymetry, water clarity, bottom type, atmospheric visibility, bioluminescence potential, beach characterization, underwater hazards, total column atmospheric water vapor, and detection and mapping of subvisible cirrus. These data support requirements for Joint Strike and Joint Littoral warfare, particularly for environmental characterization of the littoral ocean. Demonstrations of direct downlinking of near real-time data to the warfighter are also being formulated. The NEMO satellite is planned to launch in 2000 followed by an operational period of 3 to 5 years.

Keywords: imaging spectrometry, optical remote sensing, hyperspectral sensing, on-board processing

1. BACKGROUND

The Navy is in the midst of a fundamental shift away from open ocean deep water operations to joint littoral warfare. To support that effort, the Navy and Marine Corps need more precise information in denied areas regarding shallow water bathymetry, bottom type composition, detection of underwater hazards, water clarity, and visibility[1]. Visible radiation is part of the electromagnetic spectrum that penetrates the water, and passive optical systems can provide these products from space.

To address the problems of the coastal ocean, NRL scientists have been working since 1990 using the Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS)[2,3] which is operated by the Jet Propulsion Laboratory and flown on an ER-2 operated by NASA. AVIRIS data provide 20 m spatial resolution and 220 spectral bands covering a 0.4 to 2.4 µm spectral range at 10 nm resolution. In a collaborative effort with the University of South Florida, NRL has demonstrated the use of AVIRIS data to separate the chlorophyll signal from bottom reflectance in clear waters of Lake Tahoe[4] and the turbid waters offshore from Tampa Bay[5]. In addition, spectral signals from resuspended sediments and dissolved organics have been interpreted for the Tampa AVIRIS images[5,6], and for suspended sediments and kelp beds for AVIRIS images of San Pedro Channel[7]. These results lead to a general semi-analytical model for decomposition of the spectral signatures[8,9].

Similar progress has been made on the land applications of imaging spectrometer data since the value of that data was first highlighted in an article in *Science* in 1985[10]. Primarily using AVIRIS data, applications have been developed for the retrieval of atmospheric properties and for assessing crop status, environmental quality, and mineral exploration (e.g., *Remote Sensing of the Environment*, Vol. 44(2-3), Special Issue on Airborne Imaging Spectrometry). In particular, mineral exploration has become a hot topic. Several companies now provide services interpreting AVIRIS or other aircraft hyperspectral data for mineral exploration. NEMO will provide the first data from space suitable for this application.

Multispectral imagers, such as Landsat and SeaWiFS, do not have sufficient spectral bands to resolve the complex spectral signatures in the coastal ocean or the spectral signatures used for mineral exploration. Imaging spectrometers do resolve those signatures and are an ideal tool to fill these requirements, but they have not been used to date because of cost and the demands of processing the data. Both these problems have been overcome in recent years.

Multispectral sensors image several wide discontiguous spectral bands (usually 3 to 5); hyperspectral sensors image at least 60, 10 nm wide contiguous spectral bands. As defined by Goetz et al[10] each pixel within a hyperspectral image contains a continuous spectrum used to identify materials by their reflectance or emissivity. This allows identification of components within a scene (i.e., types of minerals, trees, crop health, bathymetry, composition) versus multispectral, which can only identify major features of a scene (i.e., rocks, trees, crops, water). Figure 1 gives a general description of the imaging spectrometry concept.

2. PROGRAM OBJECTIVES

The central focus of the NEMO program is to develop and fly a satellite-borne earth-imaging HSI system to provide HSI data and to process the data to meet Naval and commercial requirements. The mission objectives are as follows:

- Demonstrate use of hyperspectral imagery for the characterization of the littoral battlespace environment and littoral model development.
- Demonstrate automated, on-board processing, analysis, and feature extraction using ORASIS.
- Demonstrate the value of hyperspectral data for DoD operations and commercial applications.
- Demonstrate support to the warfighter with real-time tactical downlink of hyperspectral end products directly from the spacecraft to the field.

2.1 Naval Requirements. NEMO meets the unique requirements of Naval Forces by imaging the littoral regions of the world in 210 spectral bands over a 0.4 to 2.5 µm bandpass with a very high SNR. HRST has the goal of characterizing the dynamics of the littoral environment through the use of hyperspectral imagery and the development of coupled physical and bio-optical models of the littoral ocean. The collected images provide critical phenomenology to model the littoral environment. Specific areas of study for the Navy include water clarity, bathymetry, underwater hazards, currents, oil slicks, bottom type, atmospheric visibility, tides, bioluminescence potential, beach characterization, atmospheric water vapor, and subvisible cirrus along with terrestrial images of vegetation and soil. These data support identified requirements for Joint Strike and Joint Littoral warfare, particularly for environmental characterization of the littoral ocean and intelligent preparation of the battlespace for amphibious assault.

3. NEMO MISSION DESCRIPTION

The NEMO spacecraft will be launched into Low Earth Orbit (LEO) in 2000. The spacecraft will be placed in a sun-synchronous, 97.81° inclination orbit at 605 km altitude with a 10:30 a.m. ascending equator crossing. This orbit will provide a 7 day repeat coverage ability to allow, at a minimum, weekly access to any point on the earth. The 10:30 a.m. orbital crossing ensures consistent image quality and minimal cloud cover. Table 1 provides a general overview of the NEMO program mission characteristics.

The sensor complement flown on the NEMO spacecraft includes a Coastal Ocean Imaging Spectrometer (COIS) and a co-registered Panchromatic Imaging Camera (PIC). The primary challenges in the COIS design are the wide field of view (>2.5°) and the very high SNR, particularly near the blue end (0.4 µm) of the spectrum required for ocean imaging. NEMO also employs NRL's Optical Real-time Adaptive Spectral Identification System (ORASIS), an automated end-to-end HSI data processing system that will significantly reduce the amount of data NEMO must transmit to the ground. Figure 2 shows the current NEMO sensor deck concept.

3.1 Coastal Ocean Imaging Spectrometer (COIS). The present design of the COIS instrument employs a three-mirror-off-axis anastigmat (TMA), 12 cm aperture telescope and two spectrometers to image a 30 km wide ground swath at a 30 m GSD. Table 2 provides the characteristics of the HSI sensor system. The two spectrometers used in the COIS are:

1. The Visible Near Infrared (VNIR) spectrometer that disperses the 0.4 to 1.0 µm light into 60 spectral channels (10 nm wide) and onto the Focal Plane Array (FPA). This provides a resolution of 1.0 to 1.5% of the band & 60 spectral bins.

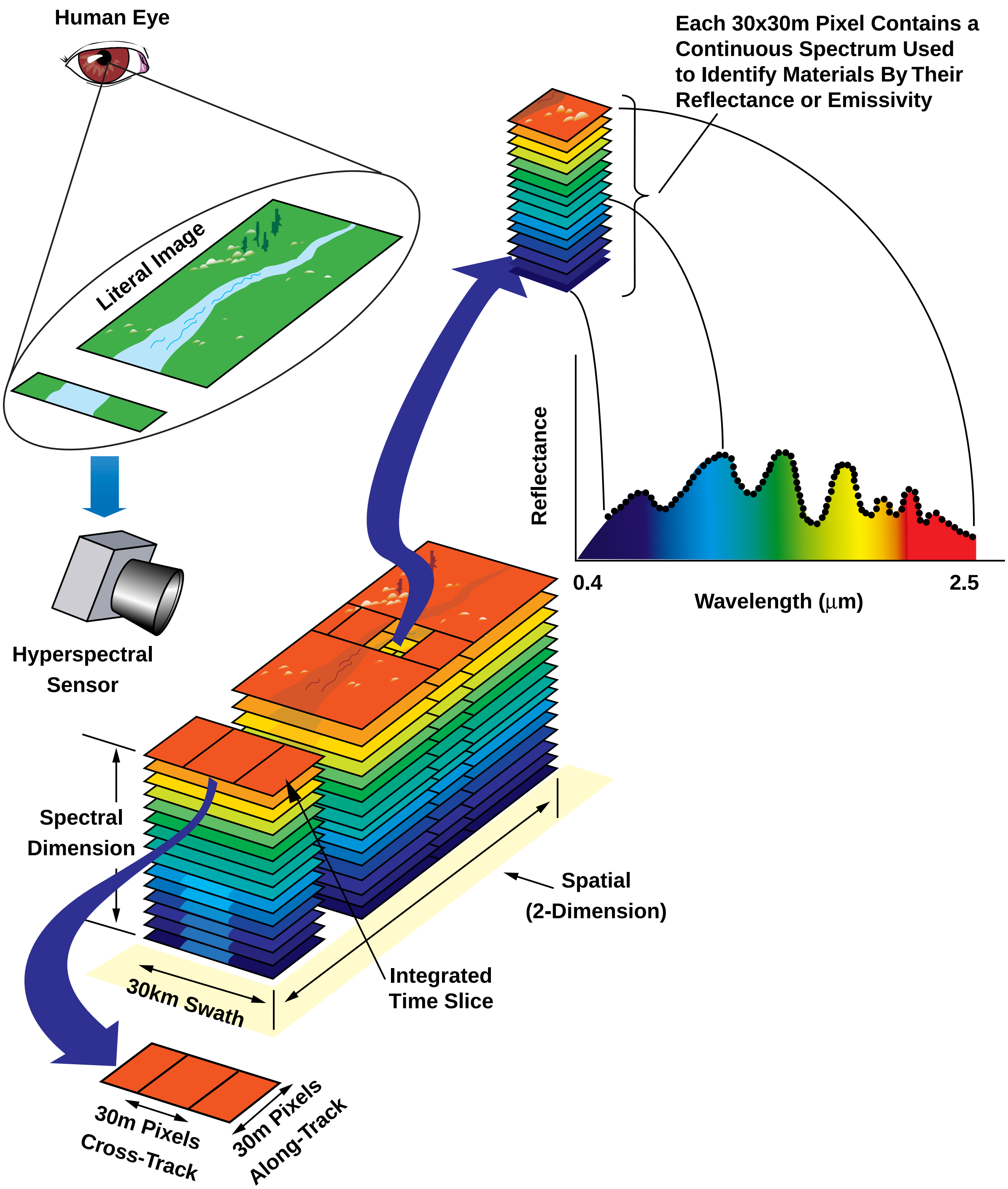

Figure 1. Imaging Spectrometry Concept

Table 1. Mission Characteristics

Item	Parameter
Launch	FY00
Orbit	• 605 km sun synchronous (97.81°) • 10:30 am Equatorial crossing (ascending)
Repeat Global Coverage	7 day repeat, 2.5 day global average reaccess
Spectral Range	0.4 to 2.5 µm at 10 nm spectral resolution (210 bands)
Signal-to-Noise	>200 to 1 over 0.4 to 1.0 µm for a 5% reflectance target
Lifetime	• 3 year mission life • 5 year design life
Data Rates	• 150 Mbps X-Band imagery and telemetry downlink • 1 Mbps S-Band Imagery downlink for tactical demonstration • 2 kbps S-Band command uplink
Data	• Estimated average daily imagery data ≈227 Gbits (capability of ≈500 Gbits) • 56 Gbit on-board storage
On-Board Processing	Real-Time feature extraction and classification with >10x data reduction using ORASIS

2. The Short-Wave Infrared (SWIR) spectrometer that disperses the 1.0 to 2.5 µm light into 150 spectral channels (10 nm wide) and onto the FPA. This provides a resolution of about 0.6% of the band and 150 spectral bins. To achieve high SNR performance, the SWIR requires active cooling by a cryocooler.

COIS provides very high SNR environmental products for imaging the low-reflectivity ocean surface. The NEMO spacecraft implements Ground Motion Compensation (GMC) sufficient to reduce the apparent ground speed by a factor of 5. This provides the required dwell time to give a similar high SNR at a GSD of 30 m. COIS is also capable of producing 60 m GSD, high SNR data products without GMC by using spatial binning of the hyperspectral FPAs. Figure 3 shows the baseline COIS optical design

3.2 Panchromatic Imaging Camera (PIC). The PIC is a separate instrument that uses a similar off-axis telescope to simultaneously image the same 30 km swath as the COIS instrument onto a 6000 pixel long linear array to produce a panchromatic image in the 0.45 to 0.67 µm wavelength range at a 5 m GSD. The moderate COIS GSD matches the spatial scale of natural objects in the littoral zone, while the high resolution PIC provides simultaneous context and sharpening and supports commercial land imaging requirements. The 30 km ground swath of COIS and PIC spans the near-shore land, beach, and ocean. COIS and PIC use a single optical bench to minimize optical boresite drift. Table 2 provides the characteristics of the PIC sensor system and the sensor designs are described in previous SPIE proceedings[12]. The COIS and PIC sensors are presently in fabrication by SAIC and are scheduled to be delivered in the fall of 1999.

3.3 Optical Real-time Adaptive Spectral Identification System (ORASIS). The HRST program employs NRL's automated end-to-end HSI data processing system called ORASIS. ORASIS offers automated and adaptive signature recognition capability, improving the operational efficiency to analyze both military and commercial data sets. It is important to note that while ORASIS is fully automated, it is also computationally intensive, requiring the NEMO satellite to have an on-board processor with multi-GigaFLOP capability.

ORASIS is a high-speed processing system that identifies the spectral signatures corresponding to physical objects in the scene without supervision or *a priori* knowledge. The approach is to analyze each spectra in the scene sequentially, discarding duplicate spectra, and working only with the unique spectra and the map of their location in the scene. Using convex set methods and orthogonal projection techniques each observed spectrum is then analyzed in terms of the set of vectors that represent the physically meaningful basis patterns that have combined to make the observed spectrum. Then matched filters (Filter Vectors) are created and used to demix the image[14,15].

ORASIS processing on board NEMO minimizes subsequent ground processing for data exploitation and maps of identified features, and enables the on-board production of data products. An important benefit of ORASIS processing is a greater than tenfold data compression (lossy), relieving hyperspectral data bottlenecks of on-board data storage and transmission to the

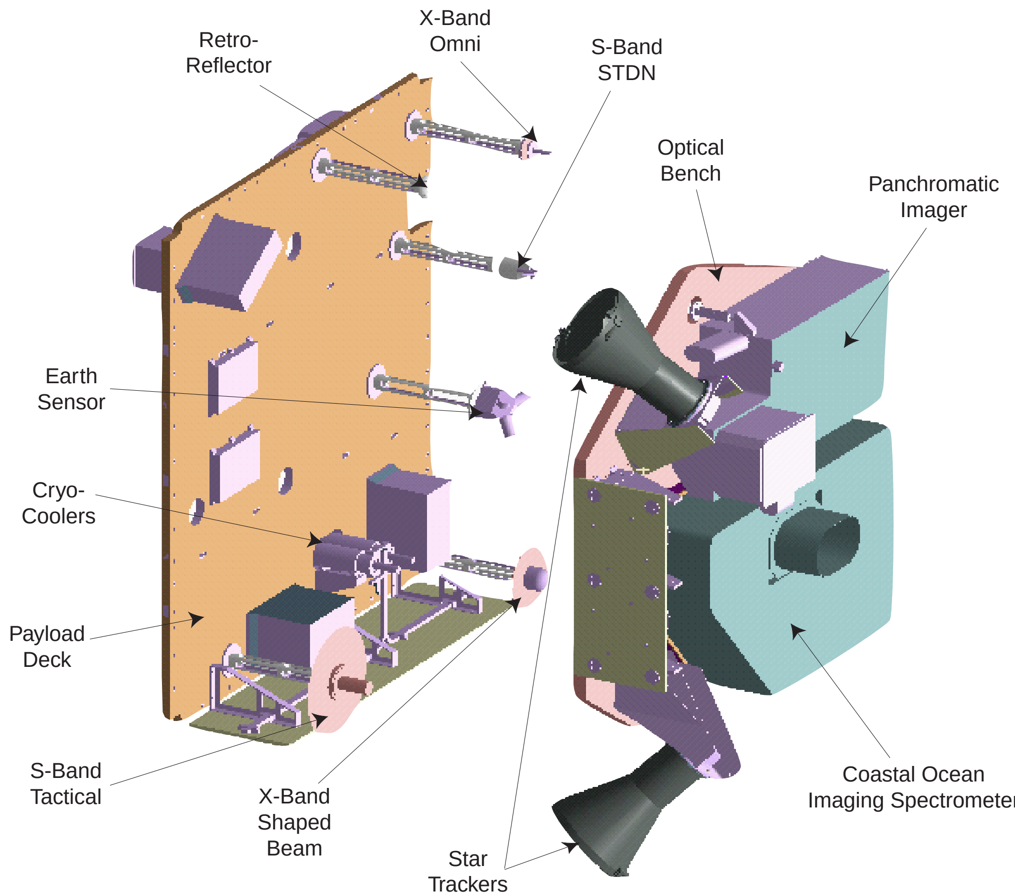

Figure 2. NEMO Sensor Deck Concept

ground. An early version of ORASIS was successfully flight demonstrated in a tactical environment in the 1996 COVERED LANTERN exercise, using hyperspectral images from a Pioneer Uncrewed Aerial Vehicle (UAV). This test proved ORASIS compression and detection capabilities.

For NEMO, ORASIS is implemented on the Imagery On-Board Processor (IOBP), an advanced high speed computer consisting of a highly parallel array of digital signal processors, capable of sustaining 2.5 GigaFLOPS. The ORASIS algorithm and the radiation tolerant IOBP allow the first demonstration of real-time processing of hyperspectral data in space. The NEMO on-board implementation of ORASIS is described in detail in another paper in this session[15]

ORASIS will also be used under the HRST program as the basic spectral decomposition tool for analyzing the HSI data and producing Naval products.

3.4 Spacecraft Characteristics. The spacecraft system architecture consists of eight hardware subsystems plus a software subsystem, which collectively accommodate the spacecraft payload and meet the mission and science requirements. These subsystems are: (i) the Attitude Determination and Control Subsystem (ADCS); (ii) the Electrical Power Subsystem (EPS); (iii) the Reaction Control Subsystem (RCS); (iv) the Thermal Control Subsystem (TCS); (v) the Structural Subsystem; (vi) the Mechanisms Subsystem; (vii) the Command, Telemetry, and Data Handling Subsystem (CT&DH); (viii) the Communications Subsystem; and (ix) the Flight Software Subsystem.

Figure 4 shows a concept of the NEMO spacecraft in orbit. Table 3 provides an overview of the subsystem characteristics of the NEMO spacecraft.

Table 2. Sensor Systems Characteristics

	VNIR	SWIR	PIC
Ground Sample Distance (GSD)	30 m with 5:1 GMC 60 m with no GMC	30 m with 5:1 GMC 60 m with no GMC	5 m (with or without GMC)
Spectral Range	0.4 to 1.0 µm	1.0 to 2.5 µm	0.545 to 0.769 µm
Spectral Bands	60	150	1
Signal to Noise Ratio	>200 to 1 @ 5% Reflectance	>100 to 1 @ 30% Reflectance	>200 to 1 @ 30% Reflectance
Swath Width	30 km	30 km	30 km
Swath Length	200 km @ 30 m GSD continuous @ 60 m GSD	200 km @ 30 m GSD continuous @ 60 m GSD	Continuous
Field of View	2.86 degrees	2.86 degrees	2.86 degrees
Ground Swath Width	30 km	30 km	30 km
Aperature Diameter	15 cm	15 cm	16.4 cm
Focal Length	36 cm	36 cm	120 cm
F#	2.4	2.4	7.32
Pixel Size	18 µm	18 µm	10 µm
# of Pixels/Spectral Band	6	6	N/A
FPA Material	Si	MCT	Si
On-Orbit Sparing	1 for 1 Spare	1 for 1 Spare	1 for 1 Spare

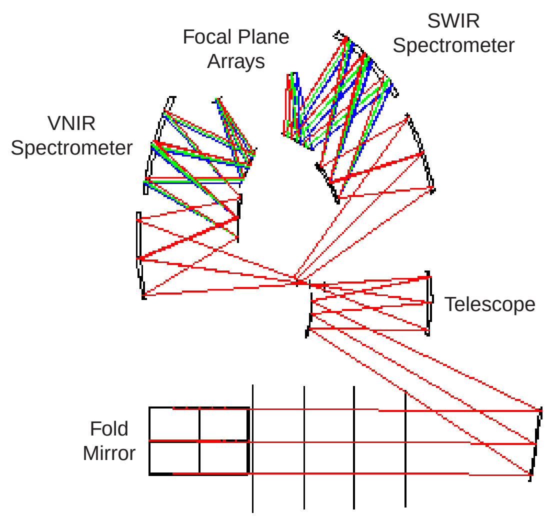

Figure 3. COIS Optical Design

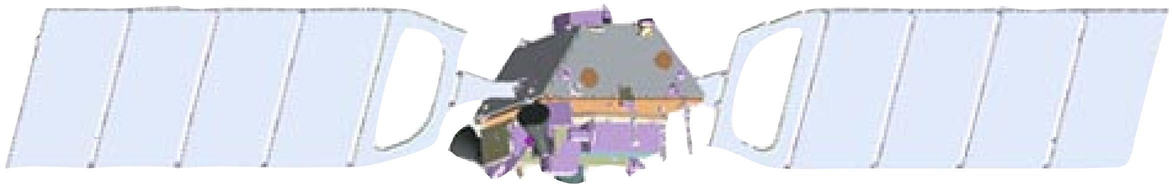

Figure 4. Spacecraft Concept

Table 3. NEMO Spacecraft Characteristics

Subsystem	Characteristics
ADCS	• 3-Axis stabilized for all modes; 0.07 degree control • Geolocation: 30 m with a Circular Error of Probability (CEP) of 0.9 • 2 star trackers and 1 inertial measurement unit for attitude determination • 4 reaction wheels and 2 electromagnetic torquers for attitude control
EPS	• 2 gimbaled (single axis) solar array panels • 4 for 3 redundant power control box • 64 Ah nickel hydrogen battery • Approximately 1500 watts
RCS	• Monopropellant hydrazine blowdown system • 1 propellant tank (76.5 kg capability) • 5 x 1N thrusters for orbit correction/orbit maintenance
TCS	• Passive thermal control with heater augmentation • Battery and payload panels thermally isolated from bus
Structures	• Primary structure is a combination of a rigid aluminum tubular frame and aluminum honeycomb shear panels • Kinematically decoupled optical bench • Space vehicle mass: ≈496 kgs dry; ≈574 kgs wet; payload ≈292 kgs
Mechanisms	• Optical bench launch restraints • Contamination covers for sensors • Solar array drive mechanisms for gimballing arrays • Launch vehicle separation • Two redundant main electrical umbilical connectors
CT&DH Subsystem	• NEMO Spacecraft Controller (NSC): Mongoose V (radiation-hardened processor) • NEMO Payload Controller (NPC): R3000 processor • Imagery On-Board Processor (IOBP): multiple SHARC processors in a parallel array • 56 Gb solid state data recorder
Communications Subsystem	• Command and Telemetry Uplink: S-Band 2kbps, 2074.18 MHz • Primary Imagery Data Downlink: X-Band 131 Mbps 8.2 GHz, with telemetry embedded • Tactical Demonstration Imagery Downlink: S-band,1.024 Mbps 2252.5MHz
Software	• On-board task scheduling capability • Embedded fault detection, isolation, and recovery (FDIR) • Attitude control interface and functionality • Spacecraft Command Language (SCL) for enhanced “macro” commanding

3.5 Mission Operations. The HRST program will use a combination of commercial operations and existing Defense infrastructure to provide the Naval, DoD, and commercial communities easy and timely access to data collected by the NEMO spacecraft. The HRST program concept for data handling on the ground is shown in Figure 5.

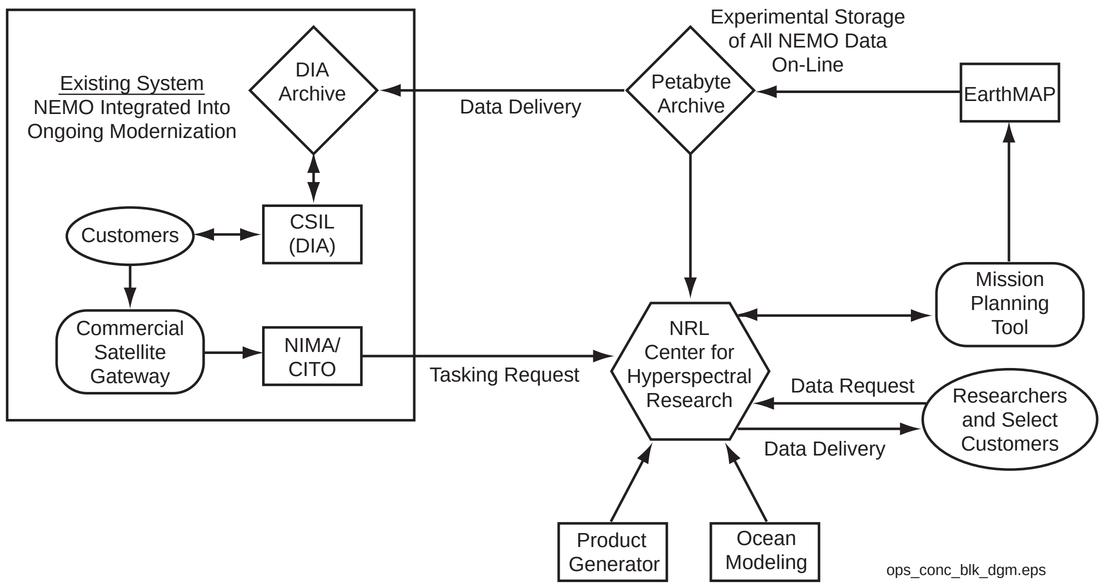

Figure 5. Ground Data Handling Concept Block Diagram

NEMO operations with be handled through the Advanced Spacecraft Operations Center (ASOC) which will be the central hub for NEMO mission planning, S/C operations, downlink data processing, command generation, and S/C and payload state-of-health monitoring.

The ASOC communicates with the S/C through Transportable Autonomous Ground Stations (TAGS) located in Fairbanks, Alaska, and at another site yet to be determined. The primary feature of the ASOC is that it consists of similar but enhanced elements of existing facilities. This approach effectively combines the cost savings benefits provided by reuse with the productivity enhancements of advanced technology. The ASOC also includes late-model, high-end work stations and PCs. These platforms have the capability to drive the operation of several automated ground stations and provide simultaneous displays for multiple satellites.

The Transportable Autonomous Ground Stations (TAGS) tracks the NEMO S/C, sends commands to the satellite from the ASOC via S-Band uplink, receives satellite health and welfare data embedded in the primary payload image data via X-Band downlink. Downlinked data is maintained on mass storage devices at the TAGS until final receipt at the Image Processing Center (IPC) is verified.

The Image Processing Center (IPC) interfaces with the ASOC to receive telemetry and imagery data. The IPC performs the image quick-look (quality control), data processing to Level 1B, and data archive functions. Activities also include fault tolerant data storage, analysis, and retrieval and in-flight sensor calibration.

The Naval Center for Hyperspectral Research (NCHR) is the Naval and scientific hub for the HRST program. The NCHR performs the tasking for the Navy of the NEMO spacecraft and data distribution function for the Naval segment of the mission, and is the focal point for Naval Hyperspectral research.

3.6 Tactical Demonstration. Currently NEMO is being designed with the ability to downlink directly to the “field” to demonstrate the use of hyperspectral data to the warfighter. An S-Band 1 Mbps transmitter along with the IOBP and ORASIS will allow real-time processing and downlinking of data products. The current demonstration scenario is as follows:

1. The NEMO spacecraft is pre-programmed with an image target command from the Fairbanks ground site.
2. The NEMO S/C enters the “demonstration area” and images the pre-programmed 30 x 5 km area. Imaging takes about 4 seconds.
3. In real-time the IOBP processes the image using the ORASIS processing algorithm. It crops the image down to a 5 x 5 km area of interest, then processes it into an ORASIS product. ORASIS reduces a 470 Mbit raw image into a much more managable 60 Mbit product.
4. The result is downlinked to a mobile field station via a 1 Mbps S-band antenna. This takes about 60 seconds.
5. A custom interface to the mobile field station will be provided by the NEMO team. This interface will have all the tools required to exploit the hyperspectral imagery.

3.7 On-Orbit Calibration and Product Validation. The HRST program requires the routine imaging of 50 sites to maintain the calibration of the COIS instrument and for the development, validation and demonstration of coastal ocean products. The use of those sites is shown schematically in Figure 5. Characterization and careful laboratory calibration to NIST standards of the COIS and PIC instruments will be conducted before flight and during thermal-vacuum testing. We will team with the instrument builder to establish the necessary tests and measurement procedures which will be incorporated as part of the instrument acceptance testing. The results will be used to create the initial calibration matrices, and software necessary to correct for any identified instrument abnormalities. On orbit COIS is designed to be stable to better than 1% per month. COIS calibration will be maintained on orbit by monthly imaging of the near full moon, daily stability checks using an on-board calibration lamp, and weekly imaging of large uniform ground reference targets, such as the Sargasso Sea and the Bonneville Salt flats, which have known and monitored reflectances. Moon imaging makes it possible to image reflected sunlight off of a known reflectance target with out having to correct for the atmosphere. The moon imaging is currently being used by the SeaWiFS program[16] and it is planned to use this approach for future NASA earth imaging systems, such as MODIS. Imaging known reflectance targets on the earth provides a means for checking the combined accuracy of calibration and atmospheric correction. NEMO will use a new atmospheric correction algorithm based on the Ahmed and Fraser[17] radiative transfer code which includes a correction for sun glint reflected off of the sea surface for water scenes[18].

An additional ten coastal ocean sites will be used for the development, and validation of the standard ocean products and models. Standard products include phytoplankton chlorophyll, colored dissolved organic matter, suspended sediments, Kd(490) (diffuse transmission of light at 490 nm), bathymetry and bottom types. Measurements of these parameters from ships and moorings will provide ground truth for validation of the algorithms. Advanced products, such as spectral absorption and beam transmission, will also be developed at these sites as part of the NRL Hyperspectral Characterization of the Coastal Ocean (HCCO) Program and the ONR Hyperspectral Coastal Ocean Dynamics Experiment (HyCODE). Those programs include the use of the NMEO products in the development and validation of coupled bio-optical physical models of the dynamics of the coastal ocean. The ultimate goal is the development of models for the prediction of the coastal ocean environment that are similar to today's weather forecasts for the atmosphere. An iterative process for the development of these models is outlined in Figure 6. The products and models will then be applied to additional sites of interest for science and naval applications

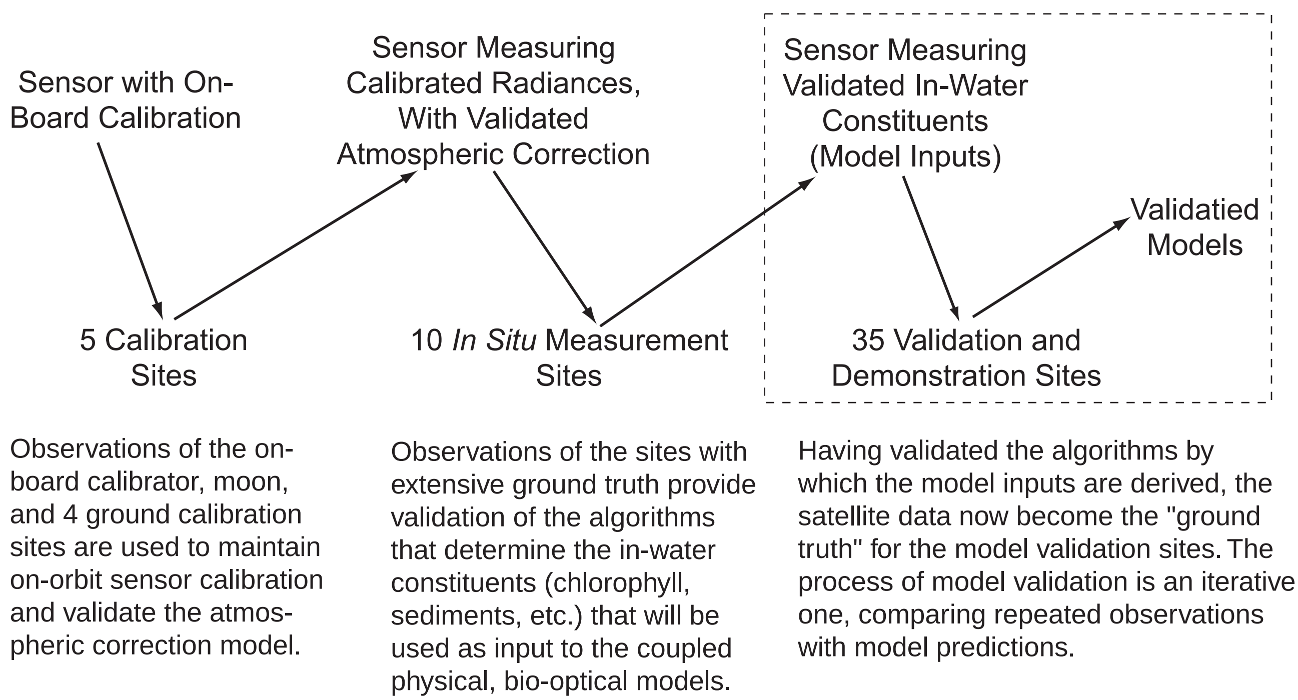

Figure 6. NEMO COIS Sensor Calibration, Product Validation and Model Development Process

4. SUMMARY

The HRST program will provide the Navy and DoD with the ability to test and demonstrate the utility of environmental hyperspectral remote sensing to support the warfighter. In addition, the HRST program along with the NEMO spacecraft provides the opportunity to apply several important technologies to dual-use remote sensing missions. These include innovations in sensors and algorithms; experience in low-cost, high-volume satellite data production; experience in small-staff, automated ground operations; and innovations in image processing and data distribution.

5. ACKNOWLEDGMENTS

We wish to thank John Antoniades, Pete Palmadesso, John Fisher, Mark Baumback and Jeff Bowles for providing insight into instrument design and the ORASIS processor. Support from Rebecca Baugh, Ron Contillo, Bob Felt, Lee J Rickard and Phil Schwartz are greatly appreciated. This work was funded by the Office of Naval Research and the Naval Research Laboratory.

6. REFERENCES

1. Marine Corps Headquarters Letter 3000 of 7 December 1992 validated by CNO (NO96) Letter 3140 Ser 960/3u567444 of 15 January 1993; Special Operations Command letter of 16 April 1991 validated by CNO (NO96) Letter 3140 Ser 960/2u567322 of 22 January 1992.
2. Porter, W.M. and H.T. Enmark, “System overview of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)”, *Proceedings of the SPIE*, V834, pp. 114-126, 1987.
3. Vane, G.R.O. Green, T.G. Chrien, H.T. Enmark, E.G. Hansen and W.M. Porter, “The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)”, *Remote Sens. Environ.*, 44, 127-143, 1993.
4. Hamilton, M.K., C.O. Davis, W.J. Rhea, S.H. Pilorz and K.L. Carder, “Estimating chlorophyll content and bathymetry of Lake Tahoe using AVIRIS data”, *Remote Sens. Environ*., 44, pp. 217-230, 1993.
5. Carder, K.L., P. Reinersman, R. Chen, F. Muller-Karager and C.O. Davis, “AVIRIS calibration and application in coastal oceanic environments”, *Rem. Sens. Environ*. 44, pp. 205-216, 1993.
6. Carder, K.L., Z.P. Lee, R.F. Chen and C.O. Davis, “Unmixing of spectral components affecting AVIRIS imagery of Tampa Bay”, *Proceedings of the SPIE*, V 1937, pp. 77-90, 1993.
7. Davis, C.O., M.K. Hamilton, W.J. Rhea and J.M. van den Bosch, K.L. Carder and R. Steward, “Spectral analysis of an AVIRIS image of San Pedro Channel”, *Proceedings of the SPIE*, V 1937, pp. 64-76, 1993.
8. Lee, Z., K.L. Carder, S.K. Hawes, R.G. Steward, T.G. Peacock and C.O. Davis, “A model for interpretation of hyperspectral remote-sensing reflectance”, *Appl. Opt*., 33(24), pp. 5721-5732, 1994.
9. Lee, Z.P., K.L. Carder, T.G. Peacock, C.O. Davis and J. Mueller, “A method to Derive Ocean Absorption Coefficients from Remote-Sensing Reflectance”, *Appl. Opt.*, 35(3), 453-462, 1996
10. Goetz, A. F. H. G. Vane, J.E. Soloman and B.N. Rock, “Imaging Spectrometry for Earth Remote Sensing”, *Science*, 228, 1147-1153, 1985
11. Gao, B-C., K. H. Heidebrecht, and A. F. H. Goetz, “Derivation of scaled surface reflectances from AVIRIS data”, *Remote Sens. Env.* 44, 165-178, 1993
12. Myers, A., “NEMO satellite sensor imaging payload”, *Proceedings of the SPIE*, V 3437, 29-40, 1998.
13. Palmadesso, P., J. Antoniades, M. Baumback, J. Bowles and L. Rickard, “Use of filter vectors and fast convex set methods in hyperspectral analysis”, Proceedings of the International Symposium on Spectral Sensing Research, November 26-December 1, 1995, Melbourne, Australia, 1996
14. Bowles, J.H., “NEMO on-board processor an ORASIS real-time hyperspectral analysis system”, *Proceedings of the SPIE*, V 3437, 20-28, 1998.
15. Bowles, J. H. , et al., "New results from the ORASIS/NEMO compression algorithm,", Proceedings of the SPIE, V 3753, In Press.
16. Barnes, R.A., R.E. Eplee , and F.S Patt., "SeaWiFS measurements of the moon", Proceedings of the SPIE, V 3498, 311-324, 1998.
17. Ahmad, Z., and R.S. Fraser, "An iterative radiative transfer code for ocean-atmosphere systems", J. Atmospheric Science, 39, 656-665, 1982.
18. Gao, B-C., M. Montes, C.O. Davis, and Z. Ahmad, "Atmospheric correction algorithm based on vector radiative transfer modeling for hyperspectral remote sensing of ocean color", Proceedings of the SPIE, V 3753, In Press